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A Relativistic Disk in Sagittarius A*

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ABSTRACT

The detection of a mm/Sub-mm “bump” in Sgr A*’s radio spectrum suggests that at least a portion of its overall emission is produced within a compact accretion disk. This inference is strengthened by observations of strong linear polarization (at the 10 percent level) within this bump. No linear polarization has been detected yet at other wavelengths. Given that radiation from this source is produced on progressively smaller spatial scales with increasing frequency, the mm/Sub-mm bump apparently arises within a mere handful of Schwarzschild radii of the black hole. We have found that a small (10-Schwarzschild-radii) magnetized accretion disk can not only account for the spectral bump via thermal synchrotron processes, but that it can also reproduce the corresponding polarimetric results. In addition, the quiescent X-ray emission appears to be associated with synchrotron self-Comptonization, while X-ray flares detected from Sgr A* may be induced by a sudden enhancement of accretion through this disk. The hardening of the flare-state X-ray spectrum appears to favor thermal bremsstrahlung as the dominant X-ray emission mechanism during the transient event. This picture predicts correlations among the mm, IR, and X-ray flux densities, that appear to be consistent with recent multi-wavelength observations. Further evidence for such a disk in Sgr A*

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is provided by its radio variability. Recent monitoring of Sgr A* at cm and mm wavelengths suggests that a spectral break is manifested at 3 mm during cm/Sub-mm flares.

The flat cm spectrum, combined with a weak X-ray flux in the quiescent state, rules out models in which the radio emission is produced by thermal synchrotron process in a bounded plasma. One possibility is that nonthermal particles may be produced when the large scale quasi-spherical inflow circularizes and settles down into the small accretion disk. Dissipation of kinetic energy associated with radial motion may lead to particle acceleration in shocks or via magnetic reconnection. On the other hand, the identification of a 106-day cycle in Sgr A*'s radio variability may signal a precession of the disk around a spinning black hole. The disk's characteristics imply rigid-body rotation, so the long precession period is indicative of a small black-hole spin with a spin parameter a/M around 0.1. It is interesting to note that such a small value of a/M would be favored if the nonthermal portion of Sgr A*'s spectrum is powered by a Blandford-Znajek type of process; in this situation, the observed luminosity would correspond to an outer disk radius of about 30 Schwarzschild radii. This disk structure is consistent with earlier hydrodynamical and recent MHD simulations and is implied by Sgr A*'s mm/Sub-mm spectral and polarimetric characteristics.

For the disk to precess with such a long (106-day) period, the angular momentum flux flowing through it must be sufficiently small that any modulation of the total angular momentum is mostly due to its coupling with the black-hole spin. This requires that the torque exerted on the inner boundary of the disk via magnetic stresses is close to the angular momentum accretion rate associated with the infalling gas. Significant heating at the inner edge of the disk then leaves the gas marginally bounded near the black hole. A strong wind from the central region may ensue and produce a scaled down version of relativistic (possibly magnetized) jets in AGNs.

Subject headings: Supermassive Black Hole, Galactic Center, Radio Astronomy.

1. Introduction

The compact radio source, Sgr A*, at the dynamical center of our Milky Way Galaxy, is believed to be associated with a supermassive black hole (Melia & Falcke 2001). Evidence

in support of this is quite compelling, especially with the detection of a 3 hour X-ray flare (Baganoff et al. 2001) from the direction of Sgr A* and the recent monitoring of a star orbiting within light-days of the black hole, which points to a central mass of $3.7 \pm 1.5 \times 10^6 M_\odot$ (Schödel et al 2002), consistent with an earlier measurements of $\sim 2.6 \times 10^6 M_\odot$ (Eckart & Genzel 1996; Ghez et al. 1998).

The nature of Sgr A* thus bears critically on our understanding of black-hole physics. Several mechanisms have been proposed over the past decade to explain its broad band spectrum and polarization, among them Bondi-Hoyle accretion (Melia 1992); a two-temperature, viscous disk (Narayan, Yi & Mahadevan 1995); a relativistic nozzle (Falcke & Markoff 2000) and a recent combination of advection-dominated disk with a nozzle (Yuan, Markoff & Falcke 2002). Over the past decade or so, our group has adopted a theoretically-motivated phenomenological approach (Melia, Liu & Coker 2000, 2001), in which the observations play a crucial role in constraining the theoretical picture.

The detection and confirmation of a mm/Sub-mm bump in Sgr A*'s spectrum suggests an emission component different from that responsible for the cm radio emission (Zylka, Mezger & Lesch 1992; Falcke et al. 1998). This emission component is also implied by Sgr A*'s variability. Radio observations show that Sgr A*'s fluctuation amplitude increases toward high frequency (Zhao & Goss 1993) and there is a spectral break at 3 mm during radio flares (Zhao et al. 2003). Since high-frequency radio emission is produced by relatively more energetic particles, located deeper in the gravitational well of the black hole (Melia, Jokipii & Narayanan 1992), the mm/Sub-mm emitting gas should be very close to the black hole's event horizon.

The detection of linear polarization in this spectral bump enhances this inference further and sets severe constraints on possible explanations for this component (Aitken et al. 2000). No significant linear polarization has yet been detected at frequencies lower than 112 GHz, though relatively strong circular polarization persists in the cm band (Bower et al. 2002). The flip of the position angle of the polarization vector by about 90° between 230 GHz and 350 GHz favors a scenario where the mm/Sub-mm emission is produced within a small, optically thin, magnetized accretion disk (Melia et al. 2000). No other model so far can explain this linear polarization characteristic (In the empirical model of Agol (2000), the frequency where the position angle flips by 90° is much lower than the frequency corresponding to the spectral peak of the flux density, which is not in line with the observations).

The existence of a small disk is also motivated theoretically. Earlier hydrodynamical simulations suggested that black-hole accretion from stellar winds, as is the case for Sgr A*, is characterized by a small angular momentum of the captured gas (Coker & Melia

1997). This accreted angular momentum is too small for the gas to settle onto a large disk, as required by the ADAF model (Narayan et al. 1995). The captured angular momentum is instead barely sufficient to circularize the gas just before it falls across the black hole’s event horizon. Detailed MHD simulations have provided an indication of the structure for such a disk (Hawley & Balbus 2002). The fact that the Magneto-Rotational Instability (Balbus & Hawley 1991) can induce a MHD dynamo in the disk provides a straightforward explanation for the mm/Sub-mm bump as the result of synchrotron process. The magnetic field also provides an anomalous viscosity and, given its strength, couples the electrons and ions via reconnection, so that a single temperature fluid is maintained (Melia et al. 2001).

X-ray observations of Sgr A* have provided additional means of learning about its nature. It turns out that Sgr A* is an extremely weak X-ray source with a quiescent X-ray luminosity of $2.2^{+0.4}_{-0.3} \times 10^{33}$ erg s^{−1} (Baganoff et al. 2001). Interestingly, electrons responsible for the mm/Sub-mm emission also Comptonize the radio photons into the X-ray band. It is notable that the physical conditions required to produce the mm/Sub-mm spectrum can also account for Sgr A*’s quiescent X-ray emission.

Chandra also detected a strong X-ray flare from the direction of Sgr A*. The flare lasted about 3 hours and featured a variation on a 10 minute time scale, suggesting an emission region no bigger than $20 r_S$, where $r_S = 7.7 \times 10^{11}$ cm is the Schwarzschild radius for the $2.6 \times 10^6 M_\odot$ supermassive black hole associated with Sgr A*. The peak flux density for this flare is 50 times higher than that in the quiescent state. Recent X-ray observations have shown that this type of X-ray flare is common to Sgr A*, occurring about once per day (Baganoff et al. 2003; Goldwurm et al. 2003).

The fact that the flares are very strong, are variable on a 10 minute time scale and have a flat spectrum, pose telling theoretical challenges which, at the same time, also create a valuable opportunity for constraining the physical conditions near the black hole’s event horizon. Our study has shown that an enhancement of the mass accretion rate through the disk can not only account for these flares, but can also induce strong Sub-mm/Far-IR flares that should occur simultaneously with the X-ray flares (Liu & Melia 2002a). Recent observations of Sgr A*’s mm/Sub-mm variability has indicated that the Sub-mm spectral index increases significantly during radio flares (Zhao et al. 2003), consistent with our prediction. However, radio flares usually last for several days, which is much longer than the duration of an X-ray flare, suggesting more complicated physical processes. Nevertheless, the nondetection of an IR flare (Hornstein et al. 2002) seems to favor this model, where X-ray flares are produced via thermal bremsstrahlung processes, over the nozzle model, in which synchrotron self-Comptonization is introduced to account for the X-ray flare emission (Markoff et al. 2001).

Moreover, the low quiescent X-ray flux also delimits hot gas content around Sgr A*. When this constraint is combined with the flat radio spectrum, one can show that the cm radio emission from Sgr A* cannot be produced by a bounded, thermal synchrotron source (Liu & Melia 2001). One possibility is that the radio emission is produced via nonthermal synchrotron processes in the region where the large scale quasi-spherical inflow circularizes to form the small accretion disk responsible for the mm/Sub-mm and X-ray emission. Energetic, nonthermal electrons can in principle be produced by the dissipation of kinetic energy associated with the radial motion of the infalling gas in shocks or magnetic reconnection. Assuming that a fixed fraction of particles is accelerated in this way, one can obtain a good fit to the radio spectrum. The circular polarization properties may then be associated with the turbulent nature of the gas in this region (see, e.g., Beckert & Falcke 2002; Ruszkowski & Begelman 2002).

On the other hand, a 106 day period in Sgr A* radio variability recently reported by Zhao et al. (2001) appears to be associated with the precession of a small hot disk under the influence of a spinning black hole (Liu & Melia 2002b). The physical characteristics of the disk indicate that it will precess as a rigid-body. However, for the disk to survive longer than the observed period, the net angular momentum flux through the disk must be extremely small, which requires that the inward angular momentum flux associated with the accreting gas must be cancelled almost completely by the outward angular momentum induced by torque associated with the magnetic stresses. A nonzero torque at the inner edge of an accretion disk has been discussed extensively (Krolik 1999; Gammie 1999; Agol & Krolik 2000) during the past few years. Recent MHD simulations have also confirmed several of these theoretical speculations (Hawley & Balbus 2002). Should this picture be correct, it should be noted that a small black hole spin of $\sim 0.1 M$, where M is the mass of the black hole, would be favored if the nonthermal portion of Sgr A*'s spectrum is instead powered by energy extracted from the black hole via a Blandford-Znajek type of process. The precession period then requires that the disk has an outer radius of $\sim 30r_S$, consistent with the general picture described above. The power extracted from the black hole also heats up the gas near the event horizon and unbinds it. The ensuing wind is not unlike the relativistic jets observed in AGNs. Further exploration of this idea may eventually reveal a more refined view of the processes hidden in the central engine of these sources.

2. A Relativistic Disk Model for the mm/Sub-mm Emission from Sgr A*

The model of a hot, magnetized, small accretion disk in Sgr A* has been developed fully in the paper by Melia et al. (2001) where, prior to the availability of all the observational

constraints described above, the inner boundary condition was chosen to have zero torque. In this instance, the temperature at the outer boundary of the Keplerian region is the primary free parameter. The disk structure is determined once one specifies the inner (r_i) and outer (r_o) radii, the magnetic (β_p) and viscous (β_ν) parameters, the mass accretion rate \dot{M} and the inclination angle of the disk. The best fit to the mm/Sub-mm polarization and spectral data is shown in Figure 1 (Melia et al. 2000). Note that here a negative percentage means that the position angle of the polarization vector is parallel to the angular momentum vector of the disk, while positive polarization means that the polarization vector flips by 90° with respect to negative polarization. The frequency at which the polarization vector flips is $\sim 3.3 \times 10^{11}$ Hz, which is higher than the peak frequency of the flux density, $\sim 2.1 \times 10^{11}$ Hz. This is a unique feature of our relativistic disk model, that is apparently not yet matched by alternative scenarios (cf. Agol 2002).

It is straightforward to understand these polarization characteristics. At mm wavelengths, the red shift side of the disk becomes optically thin first. At this point, the emission is mostly from the front and back of the black hole, where it is polarized in the direction parallel to the disk's spin axis due to the influence of the very strong toroidal field within the disk. At Sub-mm frequencies, even the gas to the front and back of the black hole becomes optically thin, and the emission from the blue shifted side of the disk dominates; the polarization vector thus flips by 90° . Faraday rotation by the intervening plasma will make the observed flip of the polarization vector different from 90° , which can reconcile the slight difference between the theoretical prediction and the observational results. Due to the relatively poor angular resolution of JCMT ($22''$ at 220 GHz), the corresponding error bars are quite big, as can be seen from Figure 1 (Aitken et al. 2000). However, the detection of strong linear polarization is quite obvious. Recent high resolution ($3.6'' \times 0.9''$) BIMA observations have confirmed strong linear polarization at 220 GHz (Bower et al. 2003), adding some confidence to the model.

3. X-ray Emission from the Relativistic Disk

Chandra observations indicate that quiescent X-ray emission from Sgr A* is very weak and soft, with an X-ray luminosity $2.2_{-0.3}^{+0.4} \times 10^{33}$ erg s $^{-1}$ and a spectral index $1.5_{-0.7}^{+0.8}$, which is not consistent with an ADAF (Baganoff et al. 2001). Given the fact that the plasma is so hot in the disk that electrons are relativistic (Melia et al. 2001), one is motivated to investigate the effects of synchrotron self-Comptonization (SSC) in this medium. Radio variability observations and recent theoretical developments (e.g., Liu & Melia 2002b) favor a nonzero stress at the inner edge of the accretion disk. We will henceforth adopt

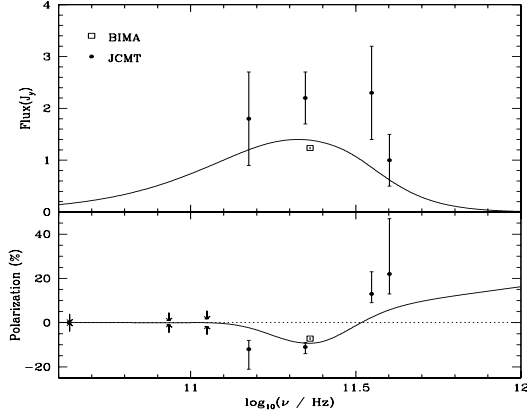


Fig. 1.— Best fit to the linear polarization of radio emission from Sgr A*. Here the model parameters are as follows: $\dot{M} = 4.1 \times 10^{16} \text{ g s}^{-1}$, $\beta_p = 0.02$, $\beta_\nu = 0.2$, $r_i = 1.8 r_s$ and $r_o = 8.5 r_s$. The inclination angle of the disk is 30° . At the outer boundary, the gas temperature is fixed by the assumption that the thermal energy of the gas equals 7% of its dissipated gravitational energy.

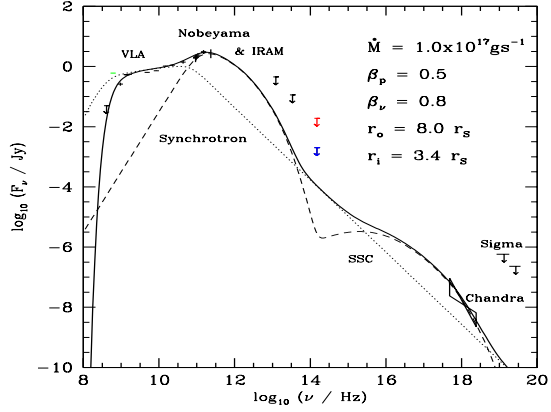


Fig. 2.— Best fit to Sgr A*'s quiescent spectrum. The model parameters are shown in the figure. Here the disk has an inclination angle of 45° . The thermal energy of the gas is assumed to equal 80% of its dissipated gravitational energy at r_o . The dashed line here denotes emission from the small disk. The dotted line gives emission produced by nonthermal particles in the circularization zone.

a zero angular momentum flux condition. The radial velocity of the accretion flow is then $v_r = -\beta_\nu \beta_p R_g T / \mu r \Omega$. The other equations derived in Melia et al. (2001) are still applicable and we won't reproduce them here. In Figure 2, we provide the best fit to Sgr A*'s broadband spectrum. SSC evidently accounts for Sgr A*'s quiescent X-ray spectrum very well.

However, Sgr A*'s X-ray emission during a flare is much more complicated than that during quiescence. Although the short variation time scale of 10 minutes is consistent with the flare being induced by an accretion process in the disk, the fact that the X-ray flux density can increase by a factor of 50 suggests dramatic changes in the disk's structure. Moreover, the hardening of the X-ray spectral index also rules out SSC as the dominant X-ray emitting mechanism during the flare (Liu & Melia 2002a). We note that the hot disk described here is not stable when the mass accretion rate is large. When \dot{M} increases, bremsstrahlung cooling becomes more and more important and can be the dominant cooling mechanism. The X-ray flare may in fact be associated with enhanced thermal bremsstrahlung emission.

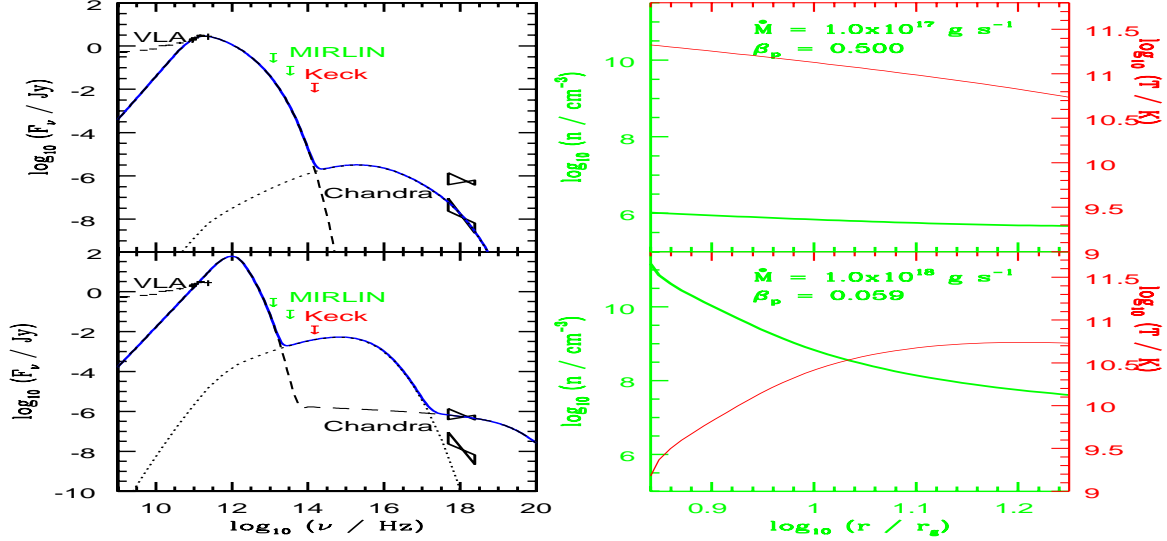


Fig. 3.— An accretion induced X-ray flare from Sgr A*. The righthand panels give the temperature (thin lines) and density profiles (thick lines) for the disk ($r_g = r_S/2$). The left panels show the corresponding disk spectra. Note that the model prediction is consistent with the IR upper limits (Hornstein et al. 2002).

Figure 3 depicts such a scenario. Here the disk has an outer radius of $9 r_S$ and we assume that the enhancement of accretion through it can suppress the MHD dynamo. A justification for this is that cooling becomes more efficient with increasing \dot{M} , and this decreases the gas temperature. We infer that β_p is thus anti-correlated with \dot{M} . During the X-ray flare, the gas density can be as high as 10^{10} cm^{-3} and the magnetic field reaches 100 Gauss. The corresponding synchrotron cooling time is a few hours, consistent with the general picture outlined above (Petrosian 1985). Recent multi-wavelength observations have indicated that there is no obvious flux change at 3 mm during the X-ray flare (Baganoff et al. 2003). According to our model, the disk is optically thick at 3 mm, so the flux density is not expected to change significantly (see Figure 3).

4. The Nature of Radio Emission from Sgr A*

In Figure 2 we showed a fit to the cm emission from Sgr A* under the assumption that this radiation is produced via nonthermal synchrotron processes in the circularization zone (the model details can be found in Liu & Melia 2001). The distribution of nonthermal particles is given by $N(E, r) = 1.7 \times 10^{-11} E^{-3.4} n(r)$, where E is the electron energy, and

$n(r)$ is the electron density at radius r . Although magnetic reconnection at smaller radii of the disk can also induce particle acceleration (adding to the contribution made by the nonthermal particles in the circularization zone), the fact that the gas temperature is as high as 10 MeV there appears to make the thermal process dominant. Nevertheless, a complete treatment of this problem incorporating particle acceleration via magnetic reconnection is warranted.

We can understand the nonthermal nature of cm radio emission using the following argument. Because quiescent X-ray emission from Sgr A* is weak (see Figure 2), we can constrain the hot gas content in Sgr A* via its bremsstrahlung emissivity. If we assume that the gas is bounded, the gas temperature must be lower than its virial value. Combining these two upper limits, one can show that to produce the 1.36 GHz flux from Sgr A* the magnetic field energy density must be more than ten times bigger than the thermal energy density of the hot gas. Such a configuration is not physical if the magnetic field is intrinsic to the hot gas. Of course, it is also possible that the radio emission is produced by some unbounded plasma, as proposed in the jet model by Markoff and Falcke (2000). Then the origin of the jet becomes the large unknown in the model.

Considering the fact that the disk surface is roughly a constant, we have $P = \pi r_o^{5/2} r_i^{1/2} [1 - (r_i/r_o)^{5/2}] / 5aM[1 - (r_i/r_o)^{1/2}]$. Setting $P=106$ days, we have $a/M = 0.088(r_i/3r_s)^{1/2}(r_o/30r_s)^{5/2}\{0.69[1 - (r_i/r_o)^{5/2}]/[1 - (r_i/r_o)^{1/2}]\}$. The precession of a larger structure would require a bigger black hole spin. We note that power extracted via a Blandford-Znajek type of process (Blandford & Znajek 1977) is then given by: $L \sim 1.1 \times 10^{34} (B/29\text{Gauss})^2 (a/0.088M)^2 (M/2.6 \times 10^6 M_\odot)^2 \text{erg s}^{-1}$, which is very close to Sgr A*'s radio luminosity. If this extracted power is responsible for radio emission from Sgr A*, then the structure of Sgr A* should be like that depicted in Figure 4.

We thus have the following picture for Sgr A*. Stellar winds in and around the Galactic center may be captured by the supermassive black hole. The small angular momentum of the captured gas leads to the formation of a small hot accretion disk near the event horizon. Mm/Sub-mm to X-ray emission is mostly produced within the small disk. Before the hot plasma falls into the black hole, however, a certain fraction of the gas is accelerated (nonthermally), either via energy extracted from a spinning black hole, or by energy liberated below the marginal stable orbit. These energetic particles then diffuse to larger radii. The flat radio spectrum is produced by these particles. The precession of the disk around the spin of the black hole can lead to a corresponding modulation of the outflow perceived in projection as well, inducing a periodic variation of the radio flux density.

The detection of a 106 day radio cycle is intriguing because it is intrinsic to Sgr A* (Zhao et al. 2001) and recent VLA observations indicate that the emission is produced within $140r_S$ (Bower et al. 2002). The dynamical time scale within such a small region is much shorter than this period, suggesting it may be associated with an intrinsic property of the black hole. Here we discuss the possibility of accounting for the periodicity with precession of the disk around a spinning black hole. Because the disk is hot and magnetized, the strong internal coupling will invalidate the Bardeen-Petterson effect (1975). However, to make the disk survive over a time scale longer than the observed period, the angular momentum flux through the disk must be close to zero (Liu & Melia 2002b). Under these conditions, it is straightforward to calculate the precession period P of such a disk around a spinning black hole.

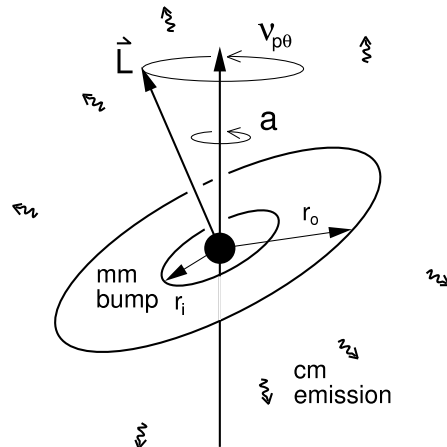


Fig. 4.— Schematic diagram of a precessing compact disk around the supermassive black hole in Sgr A*. Mm/Sub-mm to X-ray emission from Sgr A* are mostly produced within the disk. The cm radio emission, on the other hand, may be produced by diffusive nonthermal particles energized near the black hole.

5. Conclusions

Our study has shown that a hot, magnetized, relativistic accretion disk plays an essential role in revealing the nature of Sgr A*. Future observations of this source at 690 GHz (private communication with J. H. Zhao), combined with current X-ray observations, will help us to understand the interaction between the disk and the black hole, which is believed to be a key element of all AGNs. A comprehensive investigation of the supermassive black hole at the Galactic Center may eventually help us to unravel the mysterious inner workings of the most powerful engines at the nuclei of active galaxies.

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